

Excited electron contribution to the $e^+e^- \rightarrow \gamma\gamma$ cross-section

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The differential cross-section for the process $e^+e^- \rightarrow \gamma\gamma$ is calculated assuming the presence of excited electrons with a chiral magnetic coupling. This calculation permits constraining the excited electron coupling using the same theoretical framework as the one generally used for direct production searches.

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Excited electrons could be produced directly in e^+e^- collisions. They are also expected to alter the $e^+e^- \rightarrow \gamma\gamma$ differential cross-section via the diagrams shown in Fig. 1. Currently, the limits on the size of the $e^*e\gamma$ coupling obtained from direct production [1] searches are generally calculated using one form of the $e^*e\gamma$ interaction whereas limits extracted from the $e^+e^- \rightarrow \gamma\gamma$ differential cross-section [2] use a different form. By using a common theoretical framework, the $e^+e^- \rightarrow \gamma\gamma$ process can be used to extend the limits on the $e^*e\gamma$ coupling strength for excited electron masses beyond the kinematically allowed region of direct production. This paper presents a brief overview of both forms of the $e^*e\gamma$ interaction and the analytic expression for the $e^+e^- \rightarrow \gamma\gamma$ differential cross-section derived in the framework used by direct production searches. This differential cross-section is compared to the form currently in use and the impact on the limits of the $e^*e\gamma$ coupling strength is discussed.

Indirect searches, where the existence of e^* is inferred from deviations in the $e^+e^- \rightarrow \gamma\gamma$ differential cross-section, usually express limits on the $e^*e\gamma$ coupling strength assuming a general extension of the Standard Model. The interaction between an excited lepton, a lepton and a gauge boson ($\ell^*\ell V$) is described by the simplest gauge invariant form of the interaction Lagrangian [3]

$$\mathcal{L}_{\ell^*\ell V} = \frac{e}{2} \frac{\kappa}{M_{\ell^*}} \bar{\ell}^* \sigma_{\mu\nu} \ell F^{\mu\nu} + \text{h.c.} \quad (1)$$

where $F^{\mu\nu}$ denotes the electromagnetic field tensor, $\sigma_{\mu\nu}$ is the covariant bilinear tensor and M_{ℓ^*} is the mass of the excited lepton. The parameter κ is a measure of the coupling strength. The $e^+e^- \rightarrow \gamma\gamma$ differential cross-section using this purely magnetic coupling is explicitly calculated in [3] and given by

$$\begin{aligned} \left(\frac{d\sigma}{d\Omega}\right)_{e^*} &= \left(\frac{d\sigma}{d\Omega}\right)_{\text{QED}} \\ &+ \alpha^2 \left\{ \frac{1}{2} \left(\frac{\kappa}{M_{e^*}}\right)^4 (E^2 \sin^2 \theta + M_{e^*}^2) \left(\frac{q^4}{(q^2 - M_{e^*}^2)^2} + \frac{q'^4}{(q'^2 - M_{e^*}^2)^2} \right) \right. \\ &+ 4 \left(\frac{\kappa}{M_{e^*}}\right)^4 \frac{M_{e^*}^2 E^4 \sin^2 \theta}{(q^2 - M_{e^*}^2)(q'^2 - M_{e^*}^2)} \\ &\left. + \left(\frac{\kappa}{M_{e^*}}\right)^2 \left[\frac{q^2}{q^2 - M_{e^*}^2} + \frac{q'^2}{q'^2 - M_{e^*}^2} + E^2 \sin^2 \theta \left(\frac{1}{q^2 - M_{e^*}^2} + \frac{1}{q'^2 - M_{e^*}^2} \right) \right] \right\} \quad (2) \end{aligned}$$

where $\left(\frac{d\sigma}{d\Omega}\right)_{\text{QED}}$ is the Born level Standard Model differential cross-section, θ is the polar angle of one of the photons with respect to the incoming electron, E is the beam energy ($E = \sqrt{s}/2$), $q^2 = -2E^2(1 - \cos \theta)$ and $q'^2 = -2E^2(1 + \cos \theta)$. Since the two outgoing photons are indistinguishable, $\cos \theta$ is defined to be positive. Limits on the strength of the $e^*e\gamma$ coupling, κ , are expressed as a function of M_{e^*} [2].

The interaction Lagrangian of Equation 1 leads to large contributions to the anomalous magnetic moment of electrons and muons and the coupling is therefore severely constrained by existing g-2 precision measurements [4, 5]. In fact, limits from g-2 measurements are approximately an order of magnitude better than limits from $e^+e^- \rightarrow \gamma\gamma$ calculated using Equation 2.

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Limits on the $e^*e\gamma$ coupling strength from the search for directly produced excited leptons are calculated using a different theoretical framework. The effective Lagrangian describing the $\ell^*\ell V$ interaction is chosen to have a chiral symmetry which protects Standard Model leptons from acquiring large anomalous magnetic moments. This Lagrangian is generally written as [6, 7, 8, 9, 10]

$$\mathcal{L}_{\ell^*\ell V} = \frac{1}{2\Lambda} \bar{\ell}^* \sigma^{\mu\nu} \left[gf \frac{\boldsymbol{\tau}}{2} \mathbf{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] \ell_L + \text{h.c.} \quad (3)$$

where g and g' are the usual Standard Model couplings, the tensors $\mathbf{W}_{\mu\nu}$ and $B_{\mu\nu}$ represent the Standard Model gauge-invariant field tensors, $\boldsymbol{\tau}$ denotes the Pauli matrices and Y is the weak hypercharge. The compositeness scale is set by the parameter Λ which has units of energy. The size of the $\ell^*\ell V$ coupling is governed by the constants f and f' which can be interpreted as weight factors associated to the different gauge groups. In the physical basis, the Lagrangian of Equation 3 leads to the following chiral magnetic vertex [6]

$$\Gamma_{\mu}^{\ell^*\ell V} = \frac{e}{2\Lambda} f_V q' \sigma_{\mu\nu} (1 - \gamma_5) \quad (4)$$

where q' is the momentum of the gauge boson and f_V represents a particular combination of the constants f and f' for a given boson interaction. For an excited electron coupling to photon ($V = \gamma$) [6], $f_{\gamma} = -\frac{1}{2}(f + f')$. In this model, experimental limits on the $\ell^*\ell V$ coupling are usually expressed in terms of limits on $|f|/\Lambda$ as a function of the excited lepton mass for the hypothesis [11] $f = f'$ or $f = -f'[1]$.

Using this chiral magnetic interaction, the coupling is less severely constrained since contributions to the electron and muon anomalous magnetic moment are suppressed. It still however permits observable deviations in the process $e^+e^- \rightarrow \gamma\gamma$ which are not excluded by g-2 measurements. In addition, limits from indirect searches expressed in this framework could be easily compared and combined with limits coming from direct searches. To achieve this, deviations from the Standard Model $e^+e^- \rightarrow \gamma\gamma$ differential cross-section must be calculated assuming a chiral magnetic $e^*e\gamma$ coupling.

With the existence of an excited electron, the four diagrams shown in Fig. 1, contribute to the Born level production of $e^+e^- \rightarrow \gamma\gamma$ events. The differential cross-section is calculated using the $\ell^*\ell V$ vertex given in Equation 4 and combined with the standard QED interaction $e\bar{\ell}\gamma_{\mu}\ell A_{\mu}$. The excited electron propagator is taken to be the usual fermion expression with a mass M_{e^*} . Summing over the outgoing photon polarizations and neglecting the mass of the electron, the resulting differential cross-section is

$$\begin{aligned} \left(\frac{d\sigma}{d\Omega} \right)_{e^*} &= \left(\frac{d\sigma}{d\Omega} \right)_{\text{QED}} \\ &+ \frac{\alpha^2}{4} \frac{f_{\gamma}^4}{\Lambda^4} E^2 \sin^2 \theta \left[\frac{q^4}{(q^2 - M_{e^*}^2)^2} + \frac{q'^4}{(q'^2 - M_{e^*}^2)^2} \right] \\ &- \frac{\alpha^2}{8E^2} \frac{f_{\gamma}^2}{\Lambda^2} \left[\frac{q^4}{(q^2 - M_{e^*}^2)} + \frac{q'^4}{(q'^2 - M_{e^*}^2)} \right] \end{aligned} \quad (5)$$

where the same notation as for Equation 2 is used. Terms of order $(f_{\gamma}/\Lambda)^2$ in Equation 5 describe the interference between the excited electron and Standard Model diagrams.

Figure 2 shows the Standard Model Born level differential cross-section for the process $e^+e^- \rightarrow \gamma\gamma$ compared with the prediction obtained using a purely magnetic (Equation 2) and chiral magnetic (Equation 5) $e^*e\gamma$ coupling. For comparison purposes, the coupling parameters are set to $\kappa = 1$ in Equation 2, and $f_{\gamma} = 1$ and $\Lambda = M_{e^*}$ in Equation 5. The differential cross-section assuming a purely magnetic coupling is larger than the one assuming a chiral magnetic coupling.

In summary, the differential cross-section for the process $e^+e^- \rightarrow \gamma\gamma$ assuming the existence of an excited electron with chiral magnetic coupling has been calculated. The differential cross-section predictions from chiral magnetic and purely magnetic couplings are compared. Limits on the size of the $e^*e\gamma$ coupling determined from the $e^+e^- \rightarrow \gamma\gamma$ differential cross-section can be combined with limits obtained from direct production searches when the chiral magnetic form is used.

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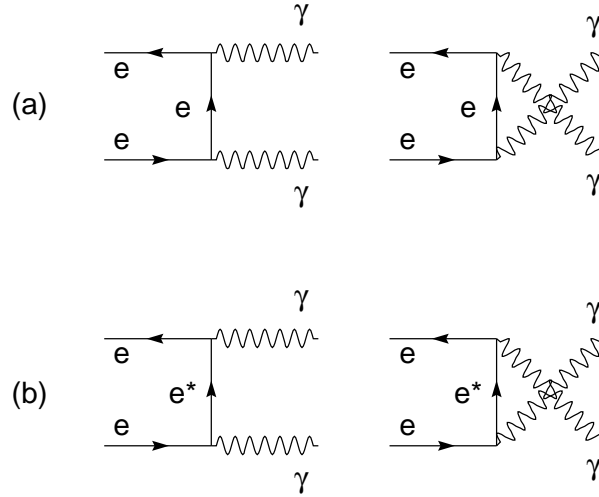


FIG. 1: Diagrams showing the (a) Standard Model and (b) excited electron contributions to the process $e^+e^- \rightarrow \gamma\gamma$.

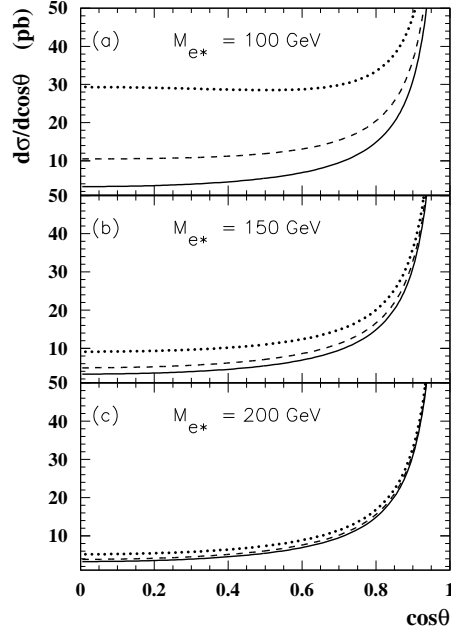


FIG. 2: Differential cross-section for the process $e^+e^- \rightarrow \gamma\gamma$. The solid lines represent the Standard Model Born level differential cross-section. The dotted lines show the prediction obtained assuming the presence of an excited electron with purely magnetic coupling assuming $\kappa = 1$ and the dashed lines represent the prediction from a chiral magnetic coupling with $f_\gamma = 1$ and $\Lambda = M_{e^*}$. The plot was generated using a center-of-mass energy of 200 GeV and with an excited electron mass of (a) 100 GeV, (b) 150 GeV and (c) 200 GeV.